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The following component part numbers comprise the compilation report:

From Safety Net to Augmented Cognition:
Using Flexible Autonomy Levels for On-Line Cognitive Assistance and Automation

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Summary

Human factors research into spatial disorientation (SD) and loss of situation awareness (SA) in the fast jet military pilot has led to consideration of systems for monitoring pilot behaviour and psychophysiology and for detection of performance degradation and incapacitation. These could be the basis of real-time countermeasures, such as a "Safety Net" system, assisting or taking over automatic control until the pilot is able to resume full control of the system. This paper looks at technologies developed under the UK MOD "Cognitive Cockpit" project for providing *cognitive assistance* through adaptive automation and decision support. The paper considers the requirements for monitoring and countermeasures for cancelling SD. It is argued that all three basic types of SD can be cancelled by effective real-time adaptive countermeasures using flexible levels of autonomy governed by pilot agreed plans. Through analysis and cognitive walk-through of a mission story-board, we show how the safety net concept can be extended by cognitive automation to provide augmentation of SA and decision making. Cognitive augmentation can be seen to mitigate the most dangerous form of insidious disorientation, by keeping the pilot in the control loop before SD sets in.

1. INTRODUCTION

Since the late 1980's, researchers in aviation human factors and medicine have been concerned about the effects of high mental workload and physiological stresses on the operators of fast-jet fighter aircraft, particularly the consequences of G-induced loss of consciousness (G-LOC), spatial disorientation (SD) and loss of situation awareness (SA). This led to consideration of the development of systems for detection of performance degradation and pilot incapacitation, and the potentially controversial concept of a "Safety Net" system, temporarily overriding the authority of the partially or fully incapacitated pilot until he/she is able to resume full control of the system. Generally, operators expressed guarded acceptance of the safety net concept, with concerns about system reliability and tactical utility of operator monitoring, advisory and recovery systems in an operational mission context. The need to override the authority of the pilot proved hard to sell.

Subsequently, many of the sub-components of the safety net system concept for providing significant risk mitigation have been successfully developed and implemented in operational systems. These include:
1) systems for automatic G-protection in aircrew life-support equipment,
2) improved sensor and computing technologies providing information fusion, situation assessment, mission management and decision support,
3) advanced control/display technologies for improved communication interfaces, and
4) new automation techniques for aircraft control and limitation of operation and performance, such as manoeuvre envelope protection, and aircraft/ground proximity warning and collision avoidance systems.

However, full implementation of the safety net concept is yet to be achieved. In particular, there remains a need to develop sufficiently reliable, trustworthy systems for the monitoring and detection of operator performance degradation (e.g. G-LOC, SD, loss of SA), that can trigger credible, effective and tactically useful interventions, preferably without the need to override the pilot's authority.

Under the UK Ministry of Defence (MOD) Applied Research Program, a three-year program of human sciences led work on intelligent pilot aiding has been recently completed at DERA Centre for Human Sciences, Farnborough. This MOD "Cognitive Cockpit" (COGPIT) project successfully demonstrated the feasibility of providing automated *cognitive assistance* to aid the fast-jet pilot through coupling adaptive automation and decision support concepts with technologies for monitoring operator behaviour and psychophysiology (1). This application of *cognitive automation* focussed on aiding in a high cognitive load scenario, with possible distraction and reduced SA, involving the use of defensive aids and mission replanning in response to a pop-up threat. A key project goal was to enhance system adaptiveness in response to dynamically changing, time pressured mission environments. Achieving this needed development of detailed understanding of the operator requirements for control and management of automated and semi-automated tasks. It was found to be essential to provide a system for task management that retains the operator's authority and executive control of critical system functions, whilst enabling delegation of responsibility to the computer for the performance of tasks as required. This would require an appropriate balance of feed-forward and feedback information on task performance. The key to this problem was two-fold:

1) The provision of systems for monitoring and reasoning with contexts (pilot state, mission, and environment) with a high degree of context sensitivity i.e. both precision and accuracy.
2) The development of a simple, readily understandable and easily controllable set of flexible *levels of autonomy* and cognitive assistance, short of full automation, with an intuitive *cognitive interface* enabling effective *cognitive interaction*.

These requirements are believed to be central to the provision of a credible, trustworthy safety net system, which can successfully intervene under G-LOC, SD or loss of SA.

The purpose of this paper is to summarise the work and lessons learnt relevant to the safety net concept, with particular reference to the use of flexible levels of autonomy and the reliability of advanced techniques for operator functional state assessment. The aim is to describe the relevance of the system concepts for cognitive augmentation mitigating against loss of SA and the onset of SD.

2. SITUATION AWARENESS AND SPATIAL DISORIENTAION

2.1 Definitions and types
SA has been defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (2). Applied to the military aviation environment, SA would include elements such as navigation, tactics, communications, weather, aircraft capability, and spatial orientation (3). It is possible for a pilot to lose situational awareness. In one study, the majority of SA errors occurred as the result of failure to perceive the situation; that is, failure to detect information or misperception of information (4). It follows that failure to perceive one's spatial orientation can result in SD, defined as an incorrect sense of the position, motion or attitude of the aircraft or of the pilot within the fixed co-ordinate system provided by the surface of the earth and the gravitational vertical (5).

The mechanism of SD is complex, involving the interaction of the vestibular and somatosensory senses in conjunction with the visual axis. Recognition of SD and subsequent recovery requires the cognition of the pilot. Traditionally SD has been categorised as Type I, when the pilot is unaware that he is disoriented; Type II, he is aware that he is disoriented; and Type III, he is aware but is unable to overcome the disorientation. Type I SD is insidiously dangerous, whereas Type II and III SD are obviously dangerous. Clearly the most dangerous condition is that of Type I SD.

In a study of USAF mishaps from 1991-2000, spatial disorientation accounted for 20.2 % of all Class A mishaps, costing over $1.4 billion and 60 fatalities. The four most common contributors to SD mishaps in decreasing order of frequency were attention management, judgement/decision making, mission demands, and psychological factors (6). Because most of the contributors involve cognitive tasks, it should be apparent

that an aircraft system that augments the cognitive ability of the pilot would decrease or eliminate the consequences of SD.

2.2 Real-time countermeasures

Initial applications of cognitive automation have focussed on aiding in a mission scenario with high cognitive load, distraction and high potential for reduced SA. A high level of SA and spatial orientation is required in military aviation in order to prosecute the mission, especially in single seat fast jets. With the increased technological ability of multiple role fighters and the capability of deploying anywhere in the world, any enhancement of a pilot's SA could provide the difference between success and failure. Today's pilots must cope with multifunction displays, multiple sensor sources, various audio inputs, avionic helmets, and real time information flowing in and out of the cockpit. Simultaneously the pilot must keep a running mental model of the mission and electronic order of battle.

In a way, this is no less true for the pilot of Unmanned Aerial Vehicles (UAV); in fact, enhancement of SA may be even more crucial since the UAV pilot is remote from the vehicle and, to some degree, out of the loop. Providing real-time feedback of the state of the UAV, the mission, and the cognitive load on the pilot is crucial to mission success. Manned or unmanned, the pilot cannot become spatially disoriented, losing the relationship of the aircraft to the earth. The consequence can be controlled (or even uncontrolled) flight into terrain. And in fighter pilot lingo, "a kill is a kill."

Cognitive automation has the capability to cancel the consequences of SD. Constantly monitoring the pilot's functional state, the aircraft and its environment, and the execution of the mission plan provides the platform for maintaining the highest degree of SA. The pilot cannot be caught in Type I SD, which essentially obviates the likelihood of controlled flight into terrain (CFIT). Even if the pilot does experience Type II SD, such as the leans, he either flies the aircraft with reference to instruments, or allows the aircraft to fly itself, based on the level of automaticity. In Type III SD, the cognitive automation should recognise that the pilot is not functioning, and the computer will take control until the pilot has recovered. If the cognitive automation prevents SD, USAF data show that $1.4 billion could be saved and 60 fatalities prevented.

3. COGNITIVE AUTOMATION

3.1 Cognitive Automation Tasks

Cognitive automation provides an intelligent assistant to the fast jet pilot. This assistant has two main goals: it must prevent the pilot from being overloaded, by doing things that he would otherwise be doing; and it must help the pilot by providing him with the information he needs, when he needs it. These goals break down into eight tasks (1):

- MONITORING PILOT: watching the pilot to see what he is doing and how he is coping with flying the mission

- MONITORING ENVIRONMENT: watching the outside world, the aircraft systems and incoming information to identify anything that the pilot needs to know or do something about

- MONITORING MISSION PLAN: keeping track of what the pilot is doing and what he needs to do in the near future

- REPLANNING MISSION: working out what should be done by the pilot in response to unexpected situations

- UPDATING MISSION PLAN: keeping the mission plan consistent and up to date

- CONFIGURING COCKPIT: making sure that the pilot has the information he needs in the form he needs it, and that the controls he is using are configured to let him do the things he wants to do quickly and easily

- DECIDING AUTOMATION: working out what tasks should be automated rather than left to the pilot

- AUTOMATING TASKS: actually carrying out various tasks for the pilot

A simplified model of the overall process within the designed system is shown in the activity diagram in Figure 1. Cognitive automation monitors three aspects of the situation:

- the environment, which includes the outside world and the state of the aircraft systems;
- the mission plan, to indicate which tasks the pilot is currently engaged in and what he will be doing shortly;
- and the pilot, to take into account his cognitive state.

These feed forward information into the replanning of the mission, the automation of tasks that have previously been identified as requiring automation and configuring the cockpit to supply the pilot with information relevant to the task he is doing. The results of monitoring the pilot, replanning the mission, automating tasks and deciding automation cause updates to the mission plan.

The performance of these activities is a continual process throughout the mission. The various aspects of the situation are continually monitored, and may result in changes in the use of displays and other output devices, in the actions recommended, and in the automation level adopted.
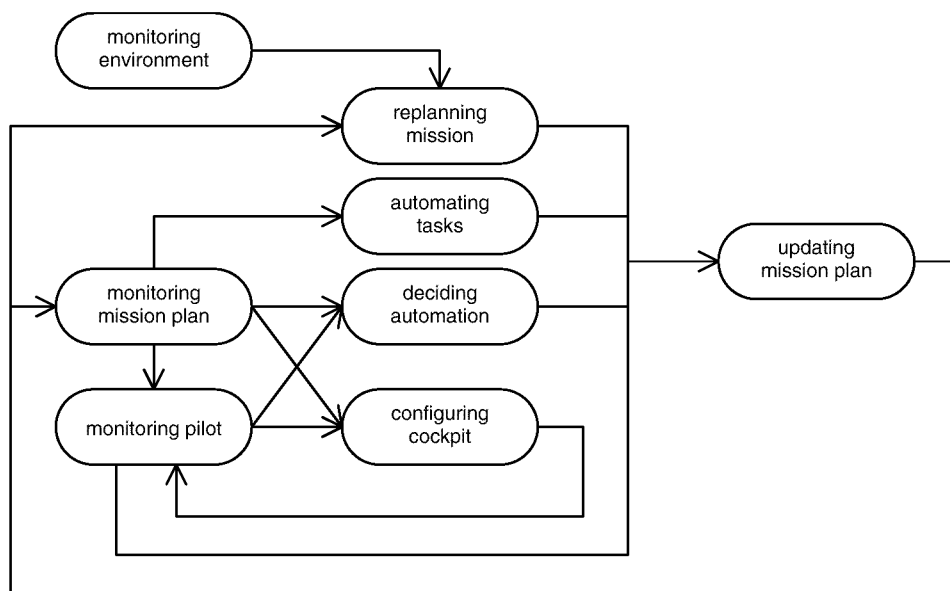

Figure 1. Cognitive automation tasks and information flows

3.2 Cognitive Automation Systems

Three classes of cognitive automation sub-systems or modules are needed to perform the goals and tasks identified above.

Situation Assessment Support System (SASS) – This is a module that monitors the status of the aircraft situation and the outside environment and recommends actions. This module is concerned with on-line mission analysis, aiding and support provided by real-time, multi-agent Knowledge Based Systems (KBS) software. This system is privy to the current mission, aircraft (e.g. heading, altitude and threat) and environmental status, and is also invested with extensive *a priori* tactical, operational and situational knowledge. Overall, this system provides information about the objective state of the aircraft within a mission context, and uses extensive KBS to aid and support pilot decisions (7). Knowledge acquisition (KA) under the COGPIT programme has focussed on the following areas:

- plan assessment - checking how the mission is progressing,
- system health - checking how the aircraft systems are performing,
- attack phase - carrying out the attack on the target,
- and Defensive Aids System (DAS) and re-routing - identifying when DAS and re-routing should be employed to counter threats and weather.

Knowledge-level models of these tasks have been built, and decision support has been implemented and successfully demonstrated for DAS re-routing in a high cognitive load scenario, with the potential for loss of SA. The SASS decision support provided the basis for augmented cognition and maintained SA. Further KA from subject matter experts is needed to build the knowledge base for implementing the correct decision support in tactical scenarios involving reduced pilot capacity and pilot incapacitation (loss of SA, SD, G-LOC). In an SD scenario, SASS would receive pertinent aircraft and environmental information (e.g. rapid accelerations, high G manoeuvres; unusual aircraft attitudes, positions, flight path trajectories; unusual rates of climb/descent, loss of altitude and energy; closure on obstacles, terrain). SASS would provide recommendations on appropriate timings and actions plans for tactically correct aircraft and mission control (e.g. automated flight control, re-routing, threat countermeasures, and terrain collision avoidance).

Cognition Monitor (COGMON) – This is a module that monitors the pilot's physiology and behaviour to provide an estimation of pilot state. This module is concerned with on-line analysis of the psychological, physiological and behavioural state of the pilot. Primary system functions include continuous monitoring of workload, and inferences about current attentional focus, ongoing cognition and intentions. It also seeks to detect dangerously high and low levels of arousal. Overall, this system provides information about the objective and subjective state of the pilot within a mission context. This information is used in order to optimise pilot performance and safety, and provides a basis for the implementation of pilot aiding (8). In an SD scenario, COGMON would receive relevant pilot information, estimate the cognitive affective state (e.g. detecting and identifying G-LOC onset, attentional focussing, overload, fatigue, drowsiness), and provide information on the pilot's ability to perform tasks (e.g. alerting, full automation).

Tasking Interface Manager (TIM) – This is a module that monitors the mission plan and manages the interface with which the pilot is presented. This module is concerned with on-line analysis of higher-order outputs from COGMON and SASS, and other aircraft systems. A central function for this system is maximisation of the goodness of fit between aircraft status, 'pilot-state' and tactical assessments provided by the SASS. These integrative functions enable this system to influence the prioritisation of tasks and, at a logical level, to determine the means by which pilot information is communicated. Overall, this system allows pilots to manage their interaction with the cockpit automation, by context-sensitive control over the allocation of tasks to the automated systems (9). The TIM functional architecture comprised modules for goal-plan tracking and for interface, timeline, automation and task management utilising a blackboard for goal-plan tracking information. In a SD scenario, TIM would receive SASS and COGMON information, identify conflicts and discrepancies, and integrate these with information on the mission plan tasks and goals. TIM would manage the implications for the performance of tasks (e.g. non-adherence to plan, non-responsiveness to planned changes), assist or automate re-planning and task performance as required, and provide the pilot with appropriate feed-forward and feedback control information.

4. MONITORING THE PILOT'S FUNCTIONAL STATE

The COGMON sub-system has a specific role within the cognitive automation system aimed at identifying the cognitive affective state of pilots, and may be seen as a means of identifying how well the pilot is coping with current task demands. This can be used to identify means of adaptively automating tasks within the cockpit environment. The COGMON uses four classes of information to estimate the cognitive affective state (Figure 2). These are physiological measures, behavioural measures, subjective measures and contextual measures. It is the key interactions between each of these classes of measures that allow predictions to be made of the type of cognitive operation being performed. When this is combined with a subjective assessment of the workload experienced by individuals when performing that specific task, and the physiological correlates of high workload, for example, then estimates of an individuals ability to cope with current task demands may be made.

Advanced flight systems also give access to the wealth of information regarding the local environment in which the pilot is operating. For example, orientation of aircraft, threat status, G experienced by pilot, altitude etc. This provides a context in which our physiological, behavioural and subjective measures can be interpreted. This information has to be more than merely of academic interest if the problems presented by

spatial disorientation are to be mediated. The output from the COGMON are designed to provide a useful index of the pilots status, and should enable principles of adaptive automation to be employed for the safe re-orientation of the pilot and aircraft.
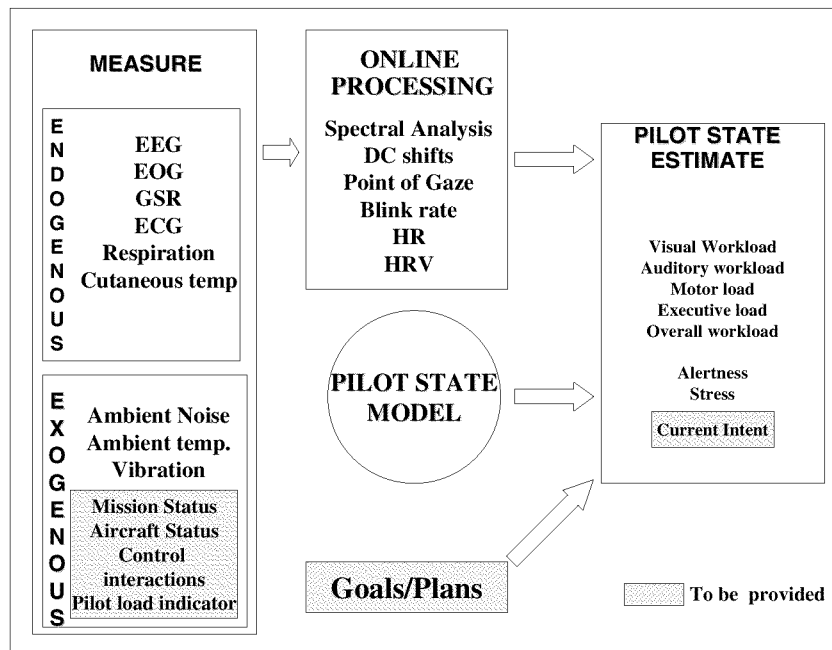
Figure 2. Structure of COGMON measures and state estimates

The spatial disorientation literature presents a picture in which conflicting visual, vestibular and proprioceptive information leads to increased disorientation. This is exacerbated by the requirement for the 'high level' forms of cognitive processing, such as those associated with strategic decision making, and attention management. Indeed it has been reported that combining unambiguous sensory information leads to reduced levels of perceived workload during the maintenance of situational and spatial awareness. The mechanism of operation of the COGMON is metaphorically illustrated below.

The situation whereby the attitude of the aircraft is nose-down, and accelerating, results in a shear force being present on the otolith organs of the inner ear. This combined with the relational movement of the direction of gravity, combines to present a perceived horizontal flight path. This illusion can be easily disambiguated if the pilot is 'head out' and can refer to the out of the window (OTW) reference frame. However if operational factors require the pilot to be head down, performing complex tasks, such as interacting with a digital map display, or calculating re-routing options, then the OTW frame of reference cannot be accessed. There is a growing body of evidence which suggest that increased levels of workload are a contributing factor to accidents involving SD. Furthermore if the task requires a high degree of attentional tunnelling, the ability to process external stimuli and 'task share' will be further diminished. Thus monitoring aircraft systems will enable the nose-down attitude and the increase in air-speed to be identified. The interaction of the pilot with the map display could indicate that focus of attention is head-down, and that attention is being invested in visuo-spatial information processing. This will also serve to limit the ability of the pilot to react to additional visuo-spatial information, and may serve to compound the disorientation instigated by the illusion of horizontal flight. Furthermore the analysis of EEG recorded over posterior and parietal scalp, those areas which overlie the areas of the brain in which visuo-spatial information is processed, shows high levels of coherence between activity recorded at parietal and occipital scalp sites. This type of activity may indicate high levels of visuo-spatial workload. This example demonstrates that available information may be integrated to develop a picture of the cognitive affective state of the pilot in which their ability to respond to external stimuli is diminished due to current task demands.

5. AUTOMATION AND CONTROL OF TASKS

5.1 Tasking Interfaces

The idea of a tasking interface exploited the lessons learnt from the US Army's RPA program (10). It arose from the need to be able to predict pilot expectations and intentions with reference to embedded knowledge of mission plans and goals. The aim was to provide an adaptive or "tasking" interface that allowed the operators/pilots to pose a task for automation in the same way that they would task another skilled crewmember. It afforded pilots the ability to retain executive control of tasks whilst delegating their execution to the automation. A tasking interface necessitated the development of a cockpit interface that allowed the pilot to change the level of automation in accordance with mission situation, pilot requirements and/or pilot capabilities. It was necessary that both the pilot and the system operated from a shared task model, affording communication of tasking instructions in the form of desired goals, tasks, partial plans or constraints that were in accord with the task structures defined in the shared task model.

Allowing pilots to choose various levels of interaction for the tasks they are required to conduct can mitigate the problem of unpredictability of automation. The TIM can utilise the monitoring and analysis of the mission tasks provided by the SASS combined with the pilot state monitoring of the COGMON to afford adaptive automation, adaptive information presentation and task and timeline management.

5.2 Contractual Autonomy

Providing flexible levels of autonomy for the performance of tasks and functions is a key requirement for implementation of the tasking interface concept. An important development under the COGPIT project was the framework devised for providing only the necessary and sufficient levels of autonomy with TIM support. The resultant framework is known as the system for pilot authorisation and control of tasks, or PACT, described in Table 1(11, 12).

Primary Modes	Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on performance
AUTOMATIC		Automatic	Full	Interrupt	Computer monitored by pilot	On/off Failure warnings Performance only if required.
ASSISTED	4	Direct Support	Advised action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action.
	3	In Support	Advice, and if authorised, action	Acceptance of advice and authorising action	Pilot backed up by the computer	Feed-forward advice and feedback on action. Alerts and warnings on failure of authorised action.
	2	Advisory	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
	1	At Call	Advice only if requested.	Full	Pilot, assisted by computer only when requested.	Feed-forward advice, only on request
COMMANDED		Under Command	None	Full	Pilot	None performance is transparent.

Table 1. Bonner-Taylor PACT framework for pilot authorisation and control of tasks

PACT is based on the idea of *contractual autonomy*. Borrowing an aircrew term from co-operative air defence, the idea is that the pilot forms a *contract,* or set of contracts, with the automation using the PACT system by allocating tasks to PACT modes and levels of automation aiding. The contract defines the nature of the operational relationship between the pilot and the computer aiding during co-operative performance of functions and tasks. Autonomy is limited by a set of contracts, or binding agreements, made between the pilot and the computer automation system governing and bounding the performance of tasks. Through PACT

contracts, the pilot retains authority and executive control, while delegating responsibility for the performance of tasks to the computer.

5.3 Control of PACT

PACT succeeds in reducing the number of automation or autonomy modes required to three - namely, fully automatic, assisted or pilot commanded - with a further four secondary levels nested within the semi-automatic, assisted mode, which can be changed adaptively or by pilot command. The PACT system uses military terminology for categories of support for Army land forces military operations (At call, advisory, in support, direct support) to afford usability and compatibility with military user cognitive schemata and models. It provides realistic operational relationships for a logical, practical set of levels of automation, reduced to six levels of autonomy, with progressive operator/pilot authority and computer autonomy supporting situation assessment, decision making and action (Figure 3). Mission functions and tasks, at different levels of abstraction allocated individually or grouped in related scripts or plays, can be set to these levels in a number of ways:

- Pre-set operator preferred defaults,
- Operator selection during pre-flight planning,
- Changed by the operator during in-flight re-planning, probably using Hands on Throttle and Stick (HOTAS), touch screen, and Direct Voice Input (DVI) commands (11).
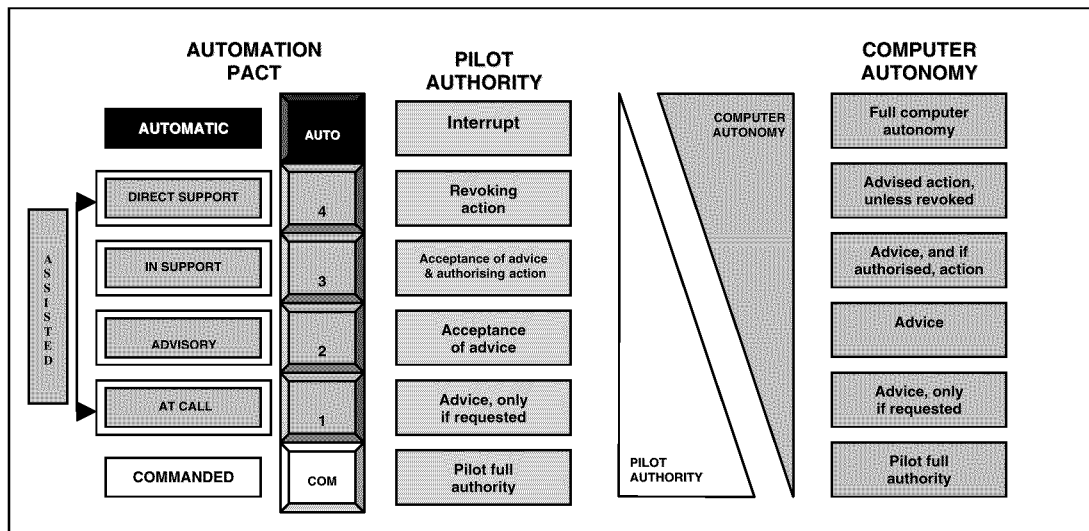- Automatically changed according to operator agreed, context-sensitive adaptive rules.

Figure 3. PACT levels of pilot authority and contractual autonomy

5.4 Intervention Strategy

An overview of the proposed adaptive intervention strategy is illustrated in Figure 4. In SD scenarios, pilot awareness is variable and unpredictable. Thus, it is important that the PACT level changes can be triggered adaptively in response to contextual input from COGMON, SASS and TIM mission goal-plan tracking (GPT), carried out in accordance with the pilot's pre-set PACT contracts. COGMON, SASS and TIM will contribute different triggering information, depending on the type of SD involved. SASS will be important for Type I SD with only weak COGMON inferences (e.g. distraction, inattention). There should be strong SASS, COGMON and TIM indications for Type II and III SD. Table 2 summarises the kinds of indications and inferences that could be available from monitoring the pilot, the environment and the mission plan in Type I, II and III SD scenarios.
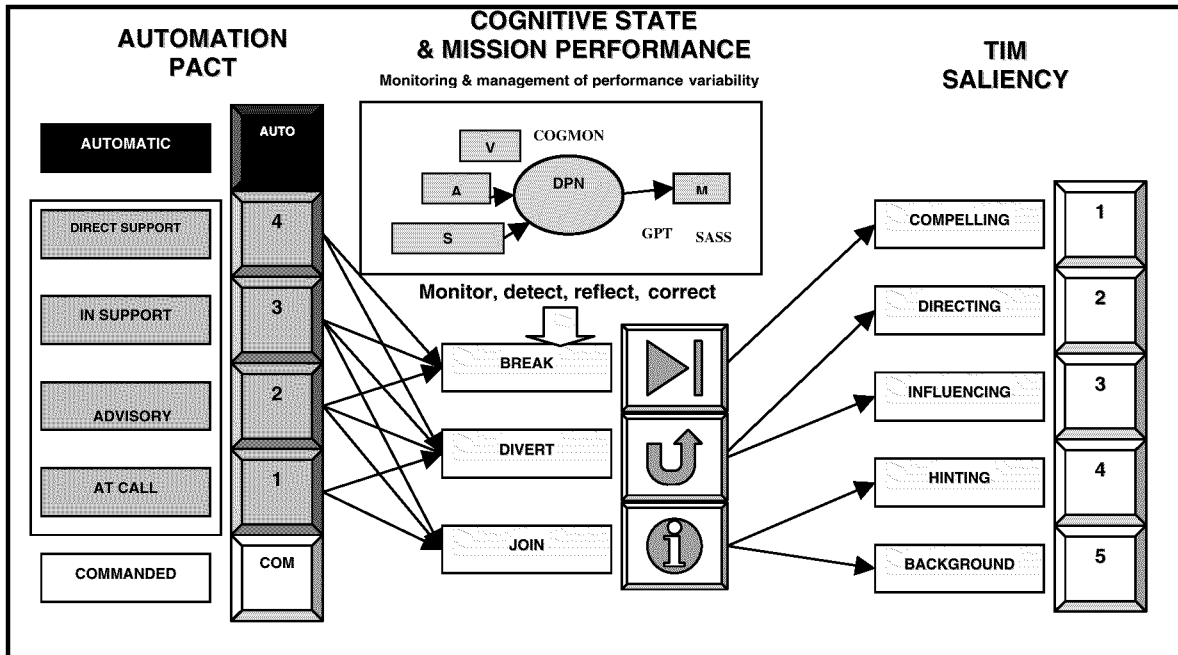
Figure 4. PACT adaptive intervention

The intervention strategy seeks to monitor and manage the variability in performance through a barrier system approach (monitor, detect, correct, reflect), and through appropriate cognitive stream interventions (join, break, divert). TIM feedback and feed-forward control messages are provided to the pilot with appropriate multi-modal intervention saliency (background, hinting, influencing, directing, compelling) developed to manage attentional and cognitive bias (13). The ability to manage the saliency TIM messages should be particularly useful for communicating adaptive countermeasure information in SD scenarios with complex sensory and cognitive demands. Different intervention saliency requirements will apply when the pilot is distracted and unaware of the problem (Type I SD), compared with when aware of conflicting sensory inputs and needing to focus (Type II SD), or when unable to overcome compelling SD (Type III SD). Figure 5 illustrates how the prototype cockpit display formats were developed to communicate TIM feed-forward and feedback control information with managed saliency in the Head Mounted Display (HMD) and Head Down Display (HDD). Auditory voice messages, with directional sound, provided powerful augmentation of the visual information.

As discussed earlier, tasks can be pre-allocated to *possible* PACT level contracts by the pilot before the flight in mission planning. The individual task PACT levels (defaults and contingencies) should be set to mitigate the risks to achievement of the individual task goals. The TIM Task Manager distinguishes between *pending, active* and *completed* tasks for the current mission element. Individual tasks progress from pending, to active and to complete as the mission progresses. An example of the Task Manager status is highlighted in the TIM control station display developed for the COGPIT demonstration (Figure 6). The panels shown in Fig 6 are clockwise, from top right, as follows:

- Inferencing Display (list of goals and tasks, indicating currently active)
- COGMON display - load estimates (green = low; yellow = medium; red = high) of pilot states (visual, verbal, auditory, spatial, left hand, right hand, motor, alertness, tactile)
- TIM Task Display - pending, active and completed tasks, with associated active or default and contingency PACT contracts, indicating the current and permitted alternative PACT levels.
- COGMAN Display - visualisation of visual, verbal, auditory, left hand, right hand loads, and location of gaze

| TASK DESCRIPTION	SD SCENARIO		
	TYPE I **Unaware** **Not responding**	**TYPE II** **Aware** **Trying to cope**	**TYPE III** **Aware-Unable to** **overcome**
MONITORING PILOT: watching the pilot to see what he is doing and how he is coping with flying the mission	*Weak COGMON indications* Behavioural: Head-down, focussed not OTW referenced. Normal, unresponsive actions e.g. map gaze location, no compensatory flight control activity, normal speech comms. Psychophysiological: Normal relaxed EEG, ECG,GSR, DC shifts, low HR, HR variability, blink. No clear inference re in or out of the loop control, or of intervention need.	*Strong COGMON indications* Behavioural: Reactive e.g. visual focussing on instruments, compensatory flight control inputs, reduced speech. Psycho-physiological: Raised alertness, high load, raised stress, focussed attention e.g. alert EEG, ECG, GSR, raised HR, HR variability, reduced blink duration, frequency. Pilot in the loop, but assistance may be appreciated.	*Clear COGMON indications* Behavioural: Scrambled or emergency procedures, speech communication Psycho-physiological – High stress, cognitive overload, sensory conflict EEG, ECG, GSR, HR, HRV, blink, gaze, nystagmus G-LOC: inaction, no speech and psycho-physiological correlates Evidence of pilot out of the loop. Assistance almost certainly required.
MONITORING ENVIRONMENT: watching the outside world, the aircraft systems and incoming information to identify anything that the pilot needs to know or do something about	*Strong SASS indications* Unexpected changes, drifts, trends in aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Orientation towards terrain, obstacles, threats. Early external indications of possible need for cautionary warning, awareness.	*Clear SASS indications* Significant departures, unusual aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Approaching terrain, obstacles, threats. Delayed or incomplete countermeasures. N.B. Does not always apply. Type II can be associated with normal flight parameters. Assistance almost certainly required.	*Clear SASS indications* Extreme, unsafe aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Immediate terrain, obstacles, threats. None or ineffective countermeasure actions. Immediate action required.
MONITORING MISSION PLAN: keeping track of what the pilot is doing and what he needs to do in the near future	*Weak TIM inferences* Current task still as planned. No clear indication that the pilot intends to take a different flight trajectory, or to change the mission plan, or that the changes are inadvertent and unintended. No clear inference of intervention need from plan/task tracking alone. Discrepancies between environment and pilot information can indicate potential awareness problem and warning need.	*Strong TIM inferences* Recognised task change. Current task not as planned, nor pending. Identifiable as priority flight control recovery action. Increased risk to mission plan. Needs assistance with recovery task and possibly in assessing the consequences for the mission plan.	*Clear TIM inferences* Current priority flight control recovery task not being performed effectively. Pilot safety and mission goals at extreme risk. Needs immediate automatic recovery of flight control and probably assistance with re-planning the mission, particularly if incapacitated.

Table 2 Monitoring SD
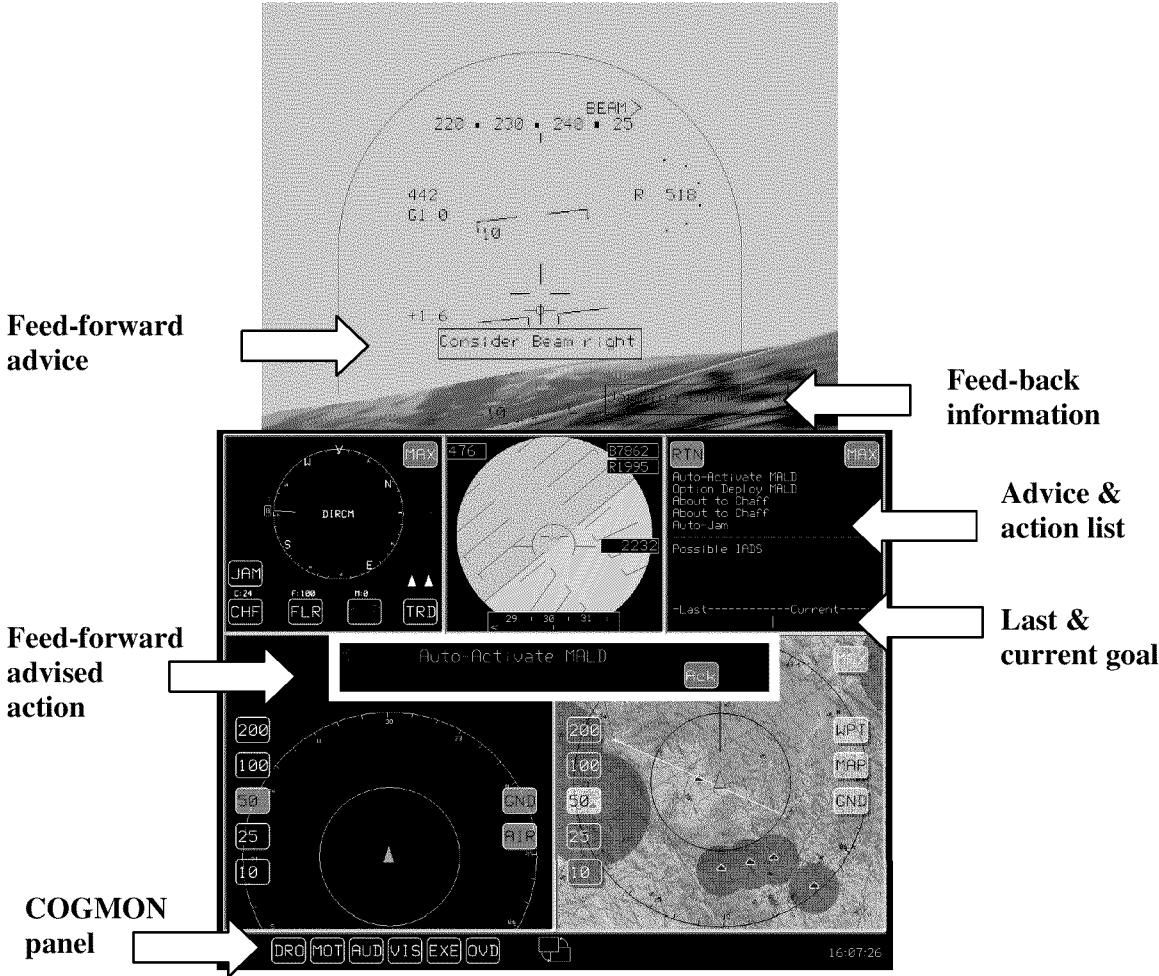
Figure 5. Prototype cockpit HDD and HMD with TIM control information.
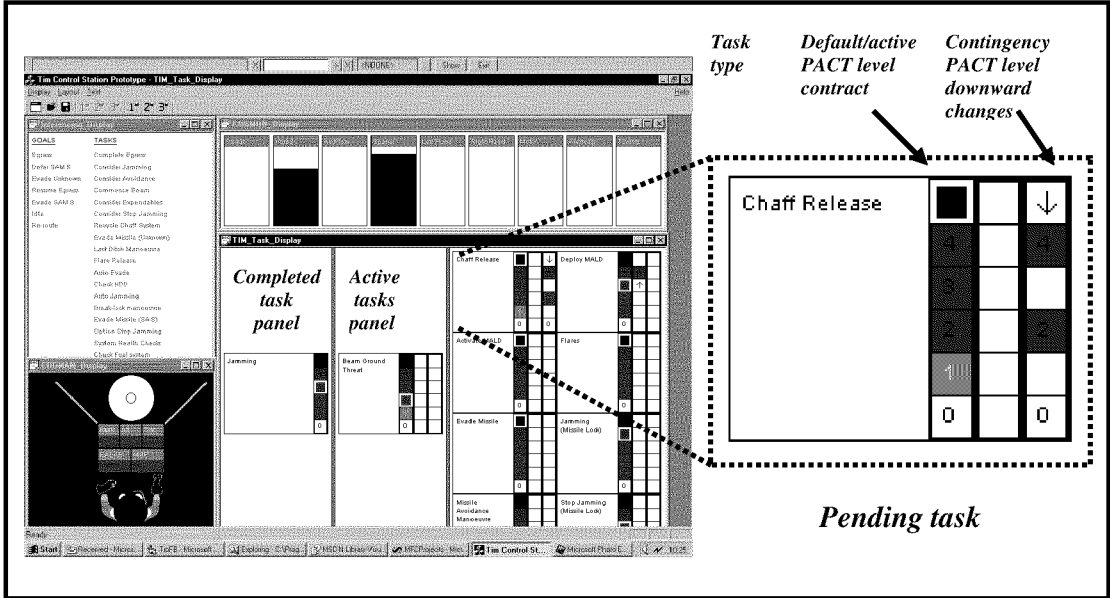

Figure 6 TIM Control station display of tasks and PACT levels

In Figure 6, the left-most panel of the TIM Task Display shows the most recently completed task ("Jamming"), whereas the active ("Beam ground threat") and pending panels ("Chaff release"; "Activate MALD" etc) show multiple tasks as necessary. Individual tasks are represented as boxes containing their name together with their associated *possible* default and contingency PACT level contracts, which range from 0 (Commanded) to 5 (Automatic). The "Chaff Release" task is highlighted with its default PACT level display set for 5 (Automatic). Two additional PACT level displays are available to the right of this default display to show contingencies for how the PACT level can change by increasing ($\uparrow$) or reducing ($\downarrow$) PACT levels according to pre-set contracts. In this example, when the default PACT level is set at 5, it is possible under certain circumstances (e.g. Chaff remaining < 30%) for the PACT level to change down to 4, 2 or 0 (but not 3 or 1). Explanatory information on the circumstances for triggering changes (contract details) is stored and available for inspection. PACT levels that are unavailable are also indicated (reverse contrast caption) as shown for pending Chaff Release task, default PACT level 1.

6. COGNITIVE AUTOMATION SD COUNTERMEASURES

In SD scenarios, pilot awareness and capacity for countermeasure action is variable and unpredictable. Table 2 has shown the indications and inferences that could be available from monitoring the pilot, the environment and the mission plan in Type I, II and III SD scenarios. In the proposed cognitive automation control system (Figure 1), these monitoring functions feed forward information into mission re-planning, the automation of tasks, and configuring the cockpit with relevant task information. In SD scenarios, these control tasks can be considered as the constituents of real-time cognitive automation SD countermeasures. Strong environment (SASS), pilot state (COGMON) and mission plan (TIM) indications are likely to be available for detecting Type II and III SD, and for guiding the kinds of countermeasures envisioned under the safety net concept. This includes the possibility of temporarily automating control of safety critical system functions, with implicit or explicit pilot consent, in the case of the partially or fully incapacitated pilot until he/she is able to resume full control of the system. For Type 1 SD, the availability of strong and sensitive environment monitoring information for comparison with pilot state and mission plan information, raises the possibility of countermeasures for this insidious and particularly dangerous form of SD, and is believed to be most significant. Type 1 and II SD countermeasures seem likely to take the form of augmenting SA, decision support and cognitive assistance i.e. designed to keep the pilot in the control loop. It seems that in considering Type 1 or II SD, where possible cognitive augmentation and assistance that keeps the pilot in the control loop, is probably always preferable to substituting, if only temporarily, fully automatic control systems for the pilot. This could be for a number of good reasons associated with risks of automation control, including loosing the tactical benefits of pilot in the loop SA, the inherent unpredictability of automation, automation mode awareness, delayed pilot recovery of control, automation bias, overuse and trust, and pilot skill fade.

Table 3 summarises the implications for Type I, II and III SD countermeasures of the cognitive automation tasks of re-planning the mission, updating the mission plan, configuring the cockpit, deciding automation, and automating tasks. It seems clear that there are significantly different implications for re-planning, cockpit configuration task management and automation, cognitive augmentation with the SD types.

- *Re-planning and Updating the Mission Plan.* Type I SD indications are unlikely to warrant immediate re-planning and task changes, but might usefully trigger cautionary warnings and advice to confirm the mission plan and task. However, TYPE II and Type III SD indications are likely to warrant checking the mission plan and flight control task. Type III SD indications may require automatic re-planning including automation of mission and flight control tasks.
- *Configuring the Cockpit.* Type I SD indications probably warrant the need for alerting cautionary and warning HMD, HDD and audio information augmenting SA, with intelligently managed saliency, and advice to check and confirm understanding of the mission and flight control status. Type II SD indications probably warrant salient feed-forward orientation and recovery information using most effective HMD, HDD, audio and tactile display cueing methods, and offer of automatic recovery options. Type III SD indications probably require provision of most salient feed-forward HMD, HDD and voice information and intuitive controls (HOTAS, DVI) for automation recovery options, and availability of pilot state feedback.

TASK DESCRIPTION	SD SCENARIO		
	TYPE I Unaware Not responding	TYPE II Aware Trying to Cope	TYPE III Aware Unable to overcome
REPLANNING MISSION: working out what should be done by the pilot in response to unexpected situations	No clear indication of immediate re-planning need. Early external indications from SASS of need for cautionary warning, and possible need to confirm the mission plan.	Inferred immediate priority task and goal change (safe recovery) with possible need to automatically check, and advise any implications for the mission plan.	Automatically assess any implications of pilot (e.g. incapacity) and aircraft state (e.g. position) for the mission plan and ability of pilot to perform tasks. Re-plan to include automation of tasks as appropriate.
UPDATING MISSION PLAN: keeping the mission plan consistent and up to date	No immediate update required.	Update mission plan if required.	Update mission plan as required.
CONFIGURING COCKPIT: making sure that the pilot has the information he needs in the form he needs it, and that the controls he is using are configured to let him do the things he wants to do quickly and easily. • Head Down Display (HDD) • Helmet Mounted Display (HMD) • Direct Voice Input (DVI) • Hands on throttle and stick (HOTAS)	Provide pilot alert/warning information. Indicate need to check information on aircraft flight control and mission plan and confirm understanding of status. Manage level of TIM f-fwd message saliency. For awareness: TIM4 Hinting or TIM3 Influencing. For immediate awareness: TIM2 Directing, or TIM1 Compelling. HMD & HDD and voice e.g. "Check attitude" or "Pull-up, pull-up".	Support f-fwd orientation and recovery action with high saliency cueing: TIM2 Directing; TIM1 Compelling Aiding options include: 1) status HMD (e.g. NDFR), HDD (e.g. BAI), 3-D audio, tactor. 2) Priority recovery action (e.g. "Pull-up, pull-up"; HMD sky pointers; directional tactors). 3) Tactically safe manoeuvre (e.g. voice "Better terrain right"). 4) Flight path director predictor (pathway in the sky). 5) Force-stick tactile cueing, +override. 6) Automatic recovery option (e.g. "Option auto pilot").	Provide information and controls for automation recovery option. Provide high saliency f-fwd information: TIM 1 Compelling. HMD,HDD & voice: "Auto avoid" "Brace, brace". Provide HOTAS manual and DVI auto selection and over-ride options. Provide pilot state indicator control panel (self report). Provide COGMON state estimation feedback information HMD, HDD and voice (TIM3 Influencing) e.g. "Reduced pilot capacity".
DECIDING AUTOMATION: working out what tasks should be automated rather than left to the pilot. • Flight Control System (FCS) • Ground Collision Avoidance System (GCAS) • Mission Control System (MCS) • Defensive Aids System (DAS) – Jamming, Manoeuvre Chaff, MALD	No immediate full auto requirement. Pre-set PACT Assisted mode level changes triggered by events (SASS): 1) FCS: PACT1 At Call to PACT2 Advisory 2) GCAS: PACT2 Advisory to PACT3 In Support 3) DAS: PACT3 In Support	Pilot selected, or pre-set PACT Assisted mode level changes triggered by events (COGMON, SASS, TIM): 1) FCS Recovery: PACT2 Advisory to PACT3 In Support 2) GCAS: PACT3 In Support to PACT4 Direct Support 3) MCS: Re-planning PACT1 At Call to PACT2 Advisory 4) DAS: PACT3 In Support to PACT4 Direct Support	Pre-set PACT Assisted mode level changes triggered by events (COGMON, SASS, TIM): 1) FCS Recovery: PACT3 In Support to PACT4 Direct Support 2) GCAS: PACT4 Direct Support 3) MCS: Replanning PACT2 Advisory to PACT4 Direct Support 4) DAS: PACT4 Direct Support
AUTOMATING TASKS actually carrying out various tasks for the pilot	*Alerting & advice.* FCS PACT2 Advisory GCAS PACT3 In Support	*Advice and action, if required.* FCS PACT3 In Support GCAS PACT4 Direct Support MCS PACT2 Advisory	*Advised action, unless revoked.* FCS PACT4 Direct Support GCAS PACT4 Direct Support MCS PACT4 Direct Support DAS: PACT 4 Direct Support

Table 3 SD Countermeasures

- *Deciding Automation and Automating Tasks.* Type I SD indications probably warrant adaptive Assisted PACT level changes to provide automatic Flight Control System (FCS) alerting and advice (PACT 2 Advisory), and raised Ground Collision Avoidance System (GCAS) support for action (PACT 3 In Support). Type II SD indications probably warrant further raising of adaptive Assisted PACT levels to provide support for both advice and action (e.g. FCS : PACT 3 In Support; GCAS: PACT4 Direct Support; DAS: PACT 4 Direct Support) and raised Mission Control System (MCS) Re-planning (PACT 2 Advisory). Type III SD indications probably warrant raising automation level of all mission and safety critical systems, including FCS recovery and MCS, to provide action, unless revoked (PACT 4 Direct Support).

7. STORYBOARD COGNITIVE WALKTHROUGH

In order to illustrate the operation of the proposed prototype cognitive automation system, a mission storyboard, route map and time-line is reported as an annex to this paper. This is a modification to the DAS Re-route storyboard used by DERA CHS for the successful MoD Final Customer Demonstration, ARP26f2.3 Automated Decision Support assignment, held at Farnborough on 23 March 2001. The scenario, events and activities are believed to be illustrative of a difficult mission with high levels of workload and stress. The level of mission difficulty is designed to defeat a pilot without adaptive aiding, cognitive automation and decision support. The story-board events and action timeline, partially illustrated in Figures 8, 9 and 10, were flown successfully and repeatedly executed by Sqn Ldr Phil O'Dell RAF, Fast-jet Project Test Pilot, DERA Boscombe Down. The storyboard builds a typical insidious Type I SD event in the context of a deep interdiction attack mission. This shows the operation of the PACT system for DAS and Re-routing automation as developed and demonstrated by DERA CHS. In summary, after executing a successful target attack in a threat environment, during the subsequent egress mission segment, the pilot encounters 2 pop-up SAM threats, which are countered using the automated DAS actions. Fusing of the 2nd SA8 close aboard leads to a fuel leak, pressurisation failure and fuel falling below chicken requiring urgent computer-assisted re-routing to safe airspace and recovery to a diversion airfield. This is followed by COGMON and TIM inferring reduced pilot capacity further triggering of changes to DAS automation levels. In the final segment illustrated in Figure 11, a Type I SD event is added to the closing reduced pilot capacity scenario. COGMON indications of stress, and TIM tracking of pilot tasks and actions. This describes adaptive cognitive automation of SD countermeasures operating in accordance with the capabilities and constraints discussed above, and identified in Tables 2 and 3. Appropriate monitoring and countermeasures for Type II SD and Type II SD are illustrated in Figures 12 and 13.

8. CONCLUSIONS

SD can be detected from monitoring environmental, behavioural and psycho-physiological indicators. It should be possible, in the near future, to implement systems that use this information together with embedded task models, to identify and to discriminate Type I, II, and II SD states. We have described how using this monitoring information, SD can be cancelled by effective real-time adaptive countermeasures, in ways that are trustworthy and that follow provably correct pilot agreed plans. An important step has been the development and successful proof-of-concept demonstration of an intuitive, easily controllable set of flexible levels of autonomy for cognitive assistance and automation. This enables the cognitive interaction needed for maintaining pilot authority and delegating responsibility to automation for the performance of tasks. Through the use of flexible levels of autonomy, the safety net concept can be extended to provide cognitive augmentation that mitigates against loss of SA before SD sets in, keeping the pilot in the control loop.

9. ACKNOWLEDGEMENTS

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ANNEX

DAS/RE-ROUTE SD STORYBOARD

The scenario is for a 2015-2020 singleton FireFox aircraft, carrier borne option, on deep interdiction, day low-level, weather dependent mission against a target airfield, with airborne refuel, SWEEP and SEAD, and with Fulchrum, SA8 and SA 14 mission threats. The pilot is Sqn Ldr Mark "Dell" Cafferky-Seares. The intelligent aiding system (TIM + SASS & COGMON) is nick-named "ODIN" after the Norse God of wisdom. The story-board segment begins in the egress phase of the mission, some 5 minutes after the successful airfield attack, as indicated on the route plan (Figure 7).
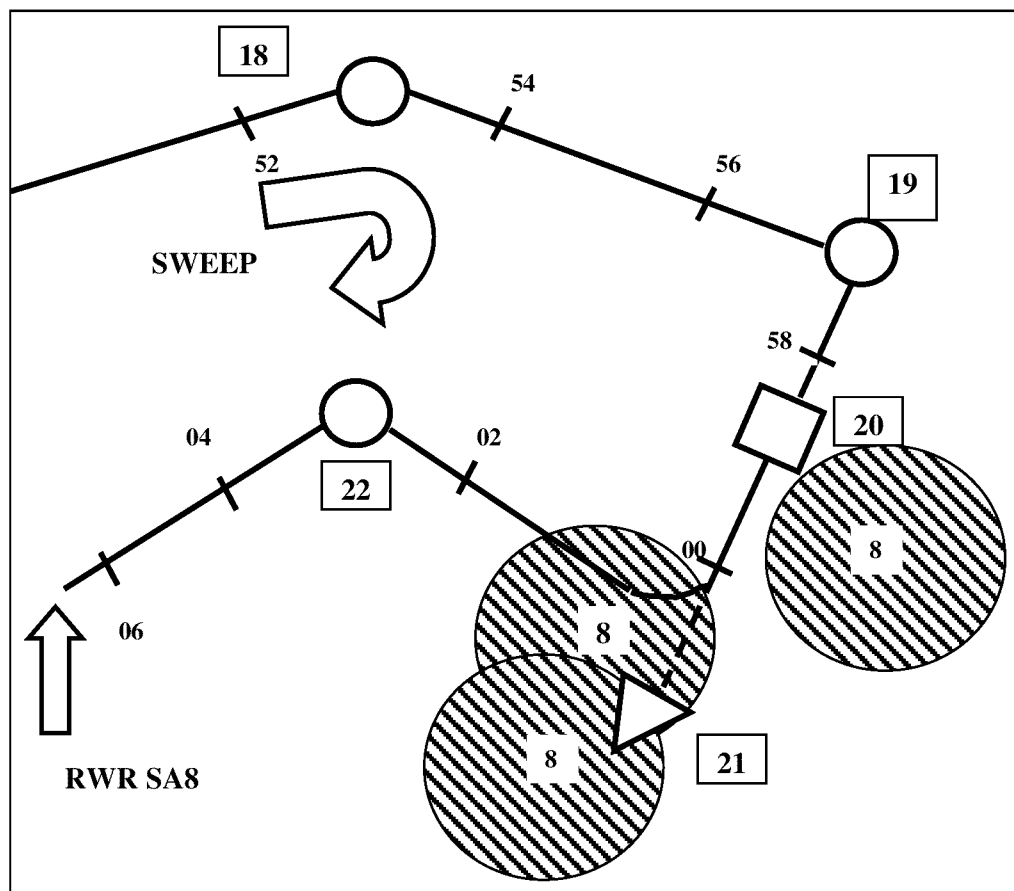
Figure 7 Route Plan for Attack and Egress

Timeline: 16:06:30 – 16:08:00 (map minutes)
Profile: Egress route flown at 100–300 AGL at 450kt.
Sensors in use: Radar (TF in a GPWS role and air-to-air), RWR, FLIR, MAW
Local Weather: 5/8th cloud at 5000ft. Visibility 10 km. Some stratus on hills above 8000ft. Surface wind 320/15.
Pilotage: Manual
Route position: Wpt 22 to 23

Pre-SD Segment

16:06:30 RWR indicates **SAM contact.** ODIN advises Dell possible Integrated Air Defence System, followed by automated DAS action (PACT3 jamming, PACT2 cued beam manoeuvre, PACT5>4 chaff, PACT3 MALD release, PACT5 stop jamming). The time-line in Figure 8 illustrates the external events and cockpit messages in this segment up to the PACT 4 deployment of chaff.
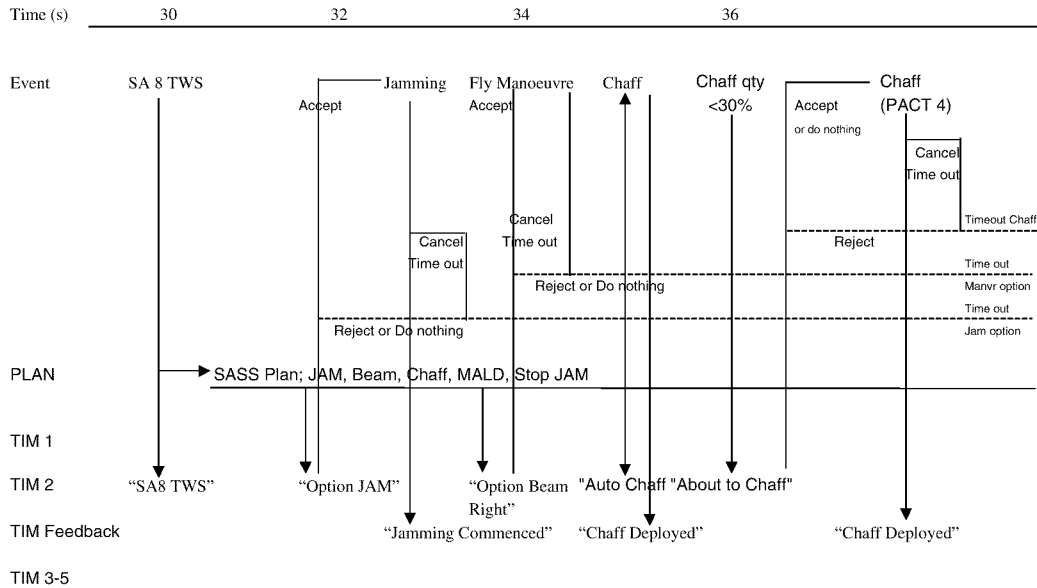
Figure 8. Time-line SA8 TWS to PACT 4 Chaff Deployed.

16:06:39 ODIN advises **Chaff failure** and Dell manual recycle of chaff system power. MAW indicates **missile inbound**, followed by ODIN automated PACT5 flares. With chaff still inoperative, ODIN (advised by COGMON) detects DELL's **inattention to missile** (gaze head-down focussed on chaff re-activation), and provides repeated **audio alert** "Missile left, unknown" (TIM1) and HDD/HMD cueing leading to Dell DVI "Acknowledged". ODIN PACT5 **auto-evade** is interrupted by Dell's manual **last ditch manoeuvre** at impact minus 5. ODIN DVO provides MAW count down "Missile impact in 6,5,4,3,2,1" followed by DIRCM activity **fusing missile** at 200 metres.

16:06:46 RWR indicates **SAM radar lock** followed by ODIN **DAS action** (PACT4 jamming, PACT2 cued 140 break lock manoeuvre). RWR indicates **SAM launch**, then MAW ODIN DVO counts down "Missile impact in 6,5,4,3,2,1" followed by Dell last ditch manoeuvre and DIRCM activity **fusing missile close** aboard, causing airframe **buffeting**.

16:07:10 SAM fire control radar ceases. ODIN PACT5 system check detects and advises **fuel leak**, followed by **pressurisation failure**, restricting ceiling to 20,000 feet, followed by **cross-feed failure**, restricting fuel **below chicken**.

The fuel loss triggers re-route calculations by ODIN (advised by SASS), which factors the fuel level of below chicken into **urgent re-route**. ODIN provides advice to Dell in HMD and HDD "Calculating re-route". Dell acknowledges this information, through DVI "Acknowledged".

SD SEGMENT

16:07:30 Key Decision Point: *Method of recovery to safe airspace*

Task: *Recover aircraft to diversion field*

ODIN provides advice to Dell in HMD and HDD to clear aircraft "Consider jettison drop tanks".

Task: *Release drop-tanks*

There is no immediate response from Dell to this ODIN advice.

Re-route level for egress is set in the mission plan at PACT 2 (Advice only). ODIN (advised by SASS) provides the information to allow presentation of proposed routes on the digital map and advises two routes to Dell recommending route A as preference. Dell requests more information on the two routes by DVI " More info route A" then "Head down 3 more info route B".

Time (s)

Event   Fuel
below Chicken

Pilot Request   Pilot Request
More Info "A"   HDD 3 More Info

Acknowledge

5" time out then 3"

PLAN   SASS; Calculate Reroute, Jettison Drop Tanks, Stipulate Recovery Profile

TIM 1

TIM 2   "Fuel Below Chicken"

TIM Feedback

TIM 3-5   "Calculating   "Consider Jettison   "2 Routes, SASS   Text Details of   Text Details of
Reroute"   Drop Tanks"   suggests Rte A"   route choice   route choice
                                                     and MAP   and MAP

Figure 9. Time-line Chicken Fuel to Re-route assessment.

ODIN provides information on each route in the HDD in sequence Route A followed by Route B, allowing Dell to toggle between maps.

Dell accepts advice for high level transit direct to diversion. Dell requests specific details on re-route A using DVI "Head down 3 details route A"

ODIN provides the detail on re-route A to Dell in HDD "Route A Climb to 20 000 ft Heading 200 deg Prepare TRD".

Task: *Gain altitude and traverse directly to diversion field;*
Task: *Prepare TRD;*
Task: *Monitor fuel supply*

Dell requests using DVI "More information pressurisation". ODIN responds HDD "Max ceiling 20000 feet due to pressurisation failure".

ODIN (advised by COGMON) interprets that Dell is suffering some degree of stress, which affects Dell's state and reduces his capability. ODIN (via COGMON) detects that Dell's gaze remains head-down on the re-route information, with sustained focussed attention, and estimates high visuo-spatial load.

ODIN's previous call "Consider release drop tanks" has produced no acknowledgement and no action response from Dell. Thus, the *release drop tanks* task remains pending.

There is no advised altitude or heading change, or Towed Radar Decoy (TRD) preparation action in response to the re-routing advice. These tasks also remain pending (advised by TIM). At this time, ODIN (advised by SASS) notes a loss of altitude.

Time (s)

Event   Pilot chooses   Pilot Request
              Route A   "More Info Pressurisation"

PLAN   → Climb 20000ft, Hdg 200°, Use TRD

TIM 1

TIM 2

TIM Feedback

TIM 3-5   Climb 20000   Hdg 200   Prep TRD   Max ceiling
                                               20000ft due Pressu Fail
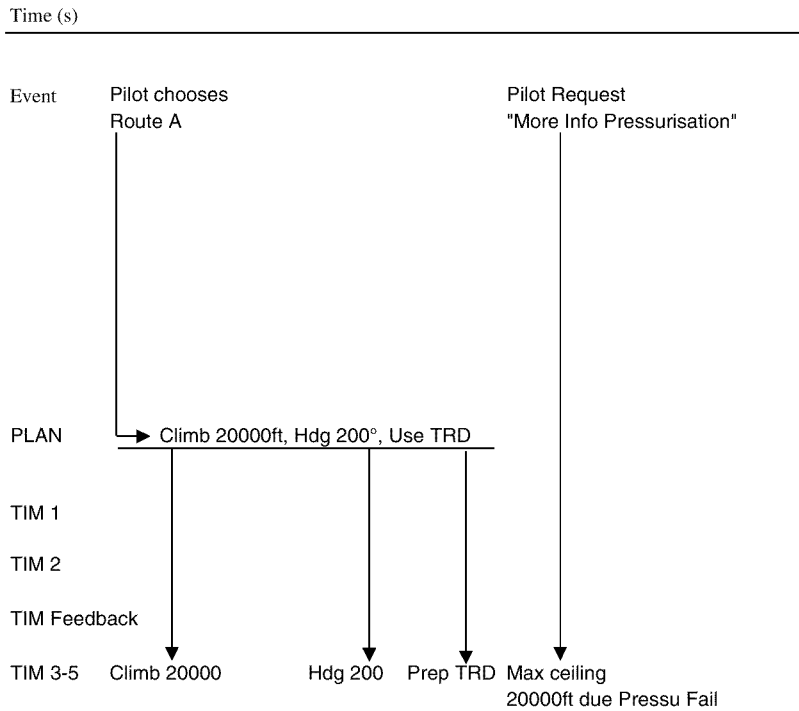
Figure 10. Time-line Re-route advice to Pressurisation query.

ODIN uses this information combined with the re-route information provided by SASS to change the level of automation, as agreed by the pilot in mission planning, and to provide SD countermeasures. The Flight Control System is changed from PACT 1 (At Call) to PACT 2(Advisory), and the pilot is notified. ODIN advises Dell by DVO "Check altitude". Dell hears and accepts the advice by DVI "Acknowledged". The Ground Collision Avoidance System is changed from PACT 2 (Advisory) to PACT 3 (In Support). ODIN advises Dell by DVO "Check flight plan". Dell accepts the advice by DVI "Accept". ODIN (via COGMON) monitors Dell visually checking the HDD SASS re-routing advice for Route A. Dell then initiates the climb to 20000ft, steers to heading 200, and initiates deployment of the TRD. ODIN (via TIM) infers the pilot's intent and current active tasks are: *Gain altitude and traverse directly to diversion field; Prepare TRD;*

As agreed by the pilot in mission planning, following an SD event, the levels of the remaining ECM countermeasures available to the aircraft are increased, as the re-route will cross a SA-6 MEZ.

The ECM automation level was set in the mission plan for egress at PACT 3 (Advice and action if authorised). ODIN assesses the pilot's capability and determines that it should be increased to PACT 4 (advice and action unless countermanded).

Flare automation is set in the mission plan for egress at PACT 3 (Advice and action if authorised). ODIN assesses the Dell's capability and determines that it should be increased to Level 4 (advice and action unless countermanded).

Missile avoidance manoeuvre automation level for egress is set in the mission plan at PACT 3 (Advice and action if authorised). Given the fuel restriction ODIN changes this automation level to PACT 2 (Advice only).

The DAS PACT information is automatically displayed on a HDD automation page. This is to allow Dell to query and/or over-ride any of the adaptive PACT changes. Dell requests information on these changes using DVI *"More information PACT change"* TIM provides advice in HMD and HDD display "Reduced pilot capacity - SD countermeasure". These monitoring and countermeasures for Type I SD are illustrated in Figure 11; possible procedures for Types II and III SD are illustrated in Figures 12 and 13.

Time (s)

Event   COGMON detects   Climb 20000, Hdg 200°, Deploy TRD   Pilot Request
                pilot under stress,   "More Info PACT
                Possible SD   Level Change

                                        Accept

                    Acknowledge

PLAN   SASS; Implement appropriate PACT level changes

TIM 1

TIM 2

TIM Feedback   "Check altitude"   "Check flight plan"

TIM 3-5   "FCS   "GCAS   "ECM PACT   "Flare PACT   "Avoidance Mnvr   "Reduced pilot
               PACT   PACT   change 3 to 4"   change 3 to 4"   change 3 to 2"   Capacity
               change   change   SD countermeasure"
               1 to 2"   2 to 3"

Figure 11. Timeline SD Type I Countermeasures.

Time (s)

Event   COGMON detects   Pitch 5°   Pitch 5°   Pitch -8°   Pilot executes   Pitch 3°   Pilot Request
                pilot under stress,   Roll Lft 25° + Roll Lft 45°+ Roll Lft 95°+ recovery   Roll 0°   "More Info PACT
                Possible SD   Alt 4000 AGL Alt 5000 AGL Alt 3000 AGL mnvr   Alt10000AGL Level Change
                Alt 250 AGL   HMD gaze   AI/HDD gaze AI/HDD gaze   Hdg 200°
                Hdg 230°   Hdg 190°   Rt Hand Stick Rt Hand Stick   HMD gaze

                             Acknowledge   Acknowledge   Acknowledge

PLAN   SASS; Implement appropriate PACT level changes

TIM 1   "Low   "Check plan"
                                             Altitude"

TIM 2   "Check   "Check   "Attitude"   "Roll
               altitude"   heading"   right"

TIM Feedback   "Pull up"

TIM 3-5   "FCS   "GCAS   "FCS   ECMPACT   FlarePACT   Avoidance   "Reduced pilot
               PACT   PACT   PACT   change   change   Mnvr   Capacity"
               change   change   change   3 to 2"   3 to 4"   change
               1 to 2"   2 to 3"   2 to 3"   3 to 2"
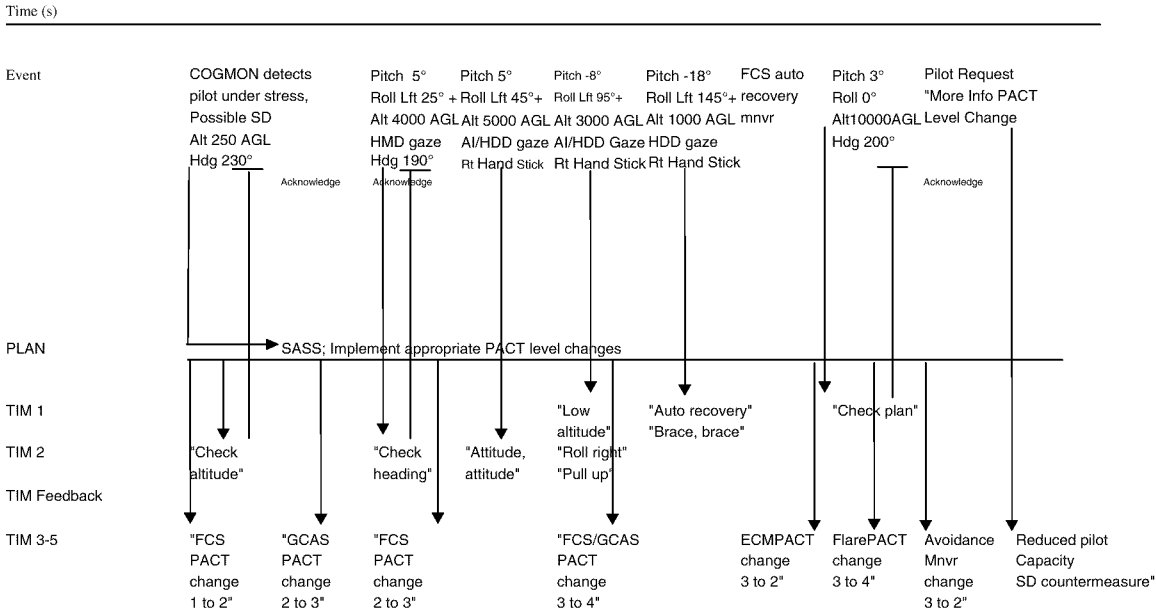
Figure 12. Timeline SD Type II Countermeasures.

Figure 13. Timeline SD Type III Countermeasures.

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